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## Control Strategy of Vapor Injection Cycle

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### ABSTRACT

Vapor refrigerant injection cycle with a flash tank has proven to be effective in improving system performance significantly at extremely low and high ambient temperatures. However, the control strategy of operating the system is still unclear. There is no open publication on the comprehensive study of the vapor injection cycle control strategy to date. This paper presents the experimental investigation on the control strategy of the vapor injection system using R410A as its working fluid. A prototype flash tank equipped with a flow visualization window was utilized to monitor and investigate the liquid-vapor separation, which guided the development of the system control strategy. The control of three valves was found to be critical to the reliable system operation: the injection port valve, the upper-stage expansion valve and the lower-stage expansion valve. The system was tested with different vapor refrigerant injection ratios under ASHRAE Standard Rating and Performance test conditions. Severe conditions of -17.8°C and 46.1°C were also used to evaluate the system behavior. The system was found to be operating steady with the liquid refrigerant in the flash tank maintaining a level of 40% to 60% of the tank height to ensure the reliable system operation.

Key words: Vapor injection, control strategy, flow visualization, liquid level

### 1. INTRODUCTION

There are two types of vapor refrigerant injection cycles: vapor injection cycle with a flash tank and vapor injection cycle with an internal heat exchanger. The cycle schematics and P-h diagrams of the two cycles are shown in Figure 1 and Figure 2, respectively. For the vapor injection cycle with a flash tank, the refrigerant discharged from the compressor flows through the condenser and then through the upper-stage expansion valve; then it is separated into liquid phase and vapor phase in the flash tank. The liquid enters the lower-stage expansion valve and then circulates through the evaporator, and enters the compressor suction. The vapor is injected to the intermediate pressure location of the compressor. In the vapor injection cycle with an internal heat exchanger, the refrigerant from the outlet of the condenser is separated into two paths. One path goes through the upper-stage expansion valve and enters the internal heat exchanger, where it provides subcooling to the refrigerant coming from the other path. The superheated vapor from the internal heat exchanger is injected to the compressor, while the sub-cooled liquid enters the lower-stage expansion valve, through the evaporator, and flows to the compressor suction. A number of studies have been conducted by different research groups to investigate the benefits of vapor injection. Ma et al. (2003, 2004) improved the heat pump cycle by employing the vapor injection cycle with an internal heat exchanger. This prototype demonstrated sufficient heating as well as high capacity water supply even at an ambient temperature of -10°C to -15°C. Compared to the conventional system, the heating capacity and the Coefficient of Performance (COP) of the vapor-injection system was improved by 8.6% and 6.0%, respectively, with an evaporating temperature of -15°C and a condensing temperature of 45°C. Wang (2008) conducted a series of testing using both the internal heat exchanger cycle and the flash tank cycle, reporting a maximum capacity and COP improvement of 33% and 23%, respectively, when the ambient temperature was -18°C. In addition, Wang (2008) tested the heat pump system in cooling mode under severe climates. It was found that the COP and capacity improvement at ambient temperature of 46°C was 5% and 15%, respectively.

Comparing the internal heat exchanger cycle and the flash tank cycle, the performance improvement is almost identical. However, the cost of a flash tank is expected to be less than that of an internal heat exchanger. Therefore, it's more favorable to use the flash tank cycle. Nevertheless, the control strategy of the flash tank cycle is somehow more complicated than the internal heat exchanger cycle, because the injected vapor leaving the flash tank is in saturated state, resulting in the dysfunction of a thermostatic expansion valve (TXV).

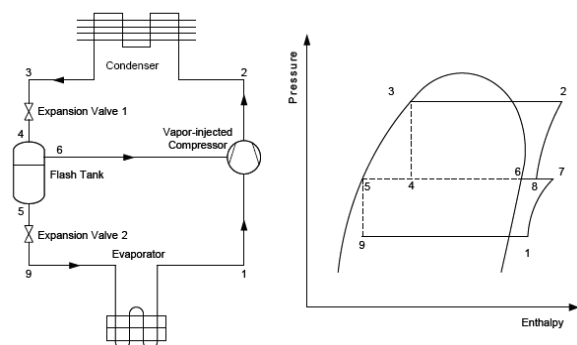


Figure 1: Schematic of a flash tank vapor injection cycle (Wang, 2008)

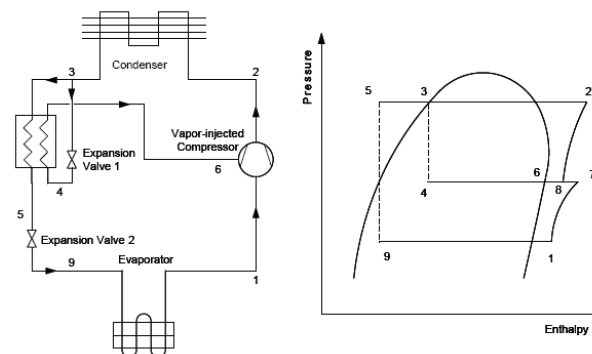


Figure 2: Schematic of an internal heat exchanger vapor injection cycle (Wang, 2008)

## 2. CONTROL STRATEGY

Three valves are critical to achieve the automatic control of the flash tank cycle: the vapor injection control valve, upper-stage expansion valve and lower-stage expansion valve as shown in Figure 3. The vapor injection control valve is necessary because it can be used to control the on/off of the vapor injection. The upper-stage expansion valve is critical to the system operation because it's closely related to the system performance. If the opening of the upper-stage expansion valve increases, the refrigerant through the valve is less expanded, decreasing the quality of the refrigerant entering the flash tank. The liquid level in the flash tank would then tend to increase. Likewise, if the opening of the upper-stage expansion valve decreases, the refrigerant through the expansion valve is further expanded, increasing the quality of the refrigerant entering the flash tank. The liquid level in the flash tank would then tend to decrease. On the other hand, increasing the opening of the upper-stage expansion valve would decrease the pressure drop across the valve, therefore raising the injection pressure in the flash tank, and vice versa. There is an optimum valve opening, which would lead to high injection pressure in the flash tank, while maintaining the liquid refrigerant in the flash tank at an appropriate level to ensure the safety of the compressor. The lower-stage expansion valve influences the evaporating pressure, which is directly related to the system performance. It also affects the evaporator outlet superheat, which needs to be maintained at a certain degree for reliable system operation. The vapor injection control valve is relatively easy to control. When the vapor injection cycle needs to be initiated, the valve can be opened. If only a conventional cycle is needed, then the valve can be closed so that the system can be operated as a conventional four-component system. Moreover, if the liquid level unexpectedly increases, and liquid refrigerant is circulating through the injection line to the compressor, then the injection control valve can be turned off to ensure the safety of the compressor. A properly functioning shut-off valve would satisfy these requirements. The control of the lower-stage expansion valve is also not difficult. The valve is closely related to the evaporating pressure, and further related to the evaporator outlet superheat. Therefore, the superheat of the evaporator outlet can be utilized to control the opening of the lower-stage expansion valve. Wang (2008) has experimentally shown that a TXV can function properly for the lower-stage expansion. Compared to the control of the two valves described above, the upper-stage expansion valve is the most difficult to control. A conventional TXV would not function properly due to the saturated state of the injected vapor, and zero degree of superheat would cause TXV hunting (Beeton and Pham, 2003). Some studies have shown that electronic expansion valve (EEV) can be used for the upper-stage expansion control (Nakamura, 2007; Saito, 2007). In practice, to reach the reliable control of the upper-stage expansion valve, control signals need to be collected and feed back to the motor which controls the opening of the valve. The control signal should refer to the liquid level of the flash tank. If the liquid level exceeds the expected limit, then the opening of the expansion valve should be decreased, raising the vapor quality entering the flash tank, and vice versa. However, the liquid level sensor and the EEV, along with other control components, would increase the overall system cost significantly. Thus, figuring out a cost-effective control strategy of the upper-stage expansion valve is crucial.

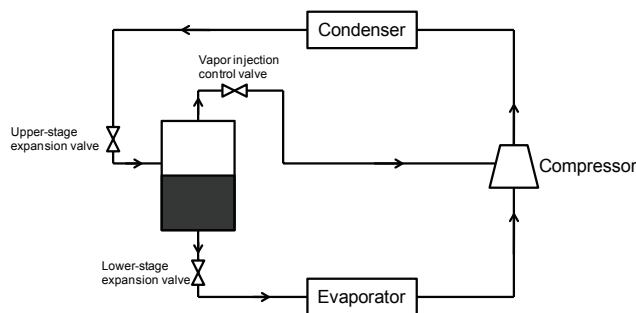


Figure 3: Schematic of the flash tank cycle with three control valves

### 3. EXPERIMENTAL SETUP

Figure 4 shows the schematic of the test facility of a vapor injection cycle with a flash tank using R410A as the refrigerant. It is comprised of a closed air loop and units located in the environmental chamber. In the closed air loop, the air is driven by the blower of the air handling unit. The air flows through the nozzle, which measures the air flow rate, and then enters the indoor unit. Within the inlet and outlet of the indoor unit, two 9-thermocouple grids measure the temperatures of the inlet and outlet air, respectively. Relative humidity sensors were also installed to measure the relative humidity of the inlet and outlet air, respectively. An outdoor unit is located in the environmental chamber. In the cooling mode, the refrigerant leaves the compressor, entering the outdoor unit for condensing. After the upper-stage expansion valve (2), the refrigerant enters the flash tank; the vapor refrigerant is injected to the compressor, meanwhile the liquid refrigerant enters the lower-stage expansion valve (4), and circulates through the indoor unit. After evaporating at the indoor unit, the refrigerant then enters the suction port of the compressor to complete the cycle. In the heating mode, the refrigerant leaving the compressor circulates through the indoor unit for condensing; then it is expanded through the upper-stage expansion valve (2), and enters the flash tank. The vapor refrigerant is injected to the compressor; meanwhile the liquid refrigerant circulates through the lower-stage expansion valve (3), evaporates in the outdoor coil, and then enters the compressor to complete the cycle. Pressure transducers and in-stream thermocouples were installed in the system to measure the refrigerant-side pressures and temperatures, respectively. Mass flow meters were installed to measure the refrigerant mass flow rate of the injected vapor and through the condenser. It should be noted that the expansion valves used in the system are manually controlled metering valves to achieve more accurate control of the system, therefore aiding the ability to investigate the control strategy of the system.

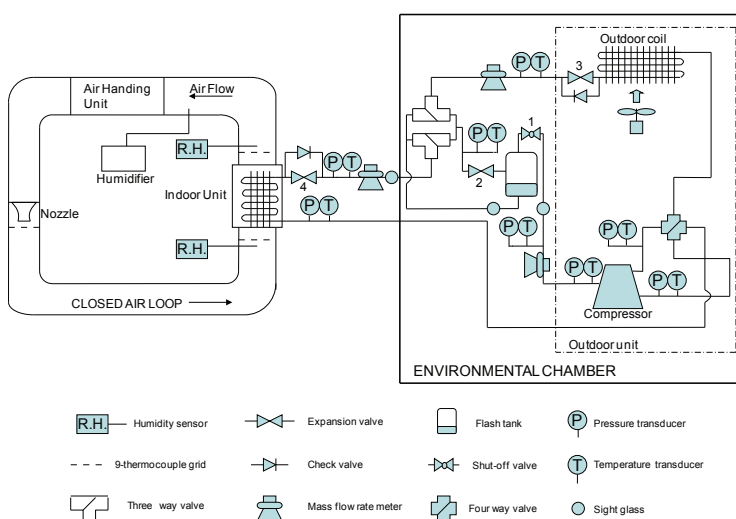


Figure 4: Schematic of the test facility of a vapor injection cycle with a flash tank

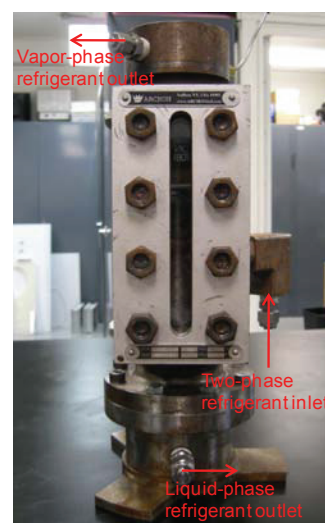


Figure 5: Schematic of the flash tank

Figure 5 shows the flash tank used in the test. The two-phase refrigerant enters the flash tank in the middle part of the tank, and then separates into liquid and vapor phases by gravity. Liquid refrigerant exits the flash tank from the port located at the bottom, and vapor refrigerant leaves the flash tank from the port at the top. A sight glass was installed in the flash tank to monitor the liquid level as well as to visualize the liquid-vapor separation in the flash tank. Specifications of the flash tank are summarized in Table 1.

Table 1: Specifications of the flash tank

Parameter	Unit	Dimension
Flash tank height	m	0.32
Diameter	m	0.07
Flash tank volume	L	1.08
Sight glass height	m	0.15

## 4. EXPERIMENTAL RESULTS AND DISCUSSIONS

### 4.1 Performance Evaluation

Both cooling and heating tests were conducted to evaluate the system performance. The volume flow rate of the air circulating in the closed air loop was set to be  $0.58 \text{ m}^3/\text{s}$  (1,240 cfm). The test conditions followed the ASHRAE Standard (1995), and illustrated in Table 2. Moreover, extended conditions of  $46.1^\circ\text{C}$  for cooling and  $-17.8^\circ\text{C}$  for heating were added to investigate the potential improvement at severe weather conditions. The injection ratio is defined as the injected vapor mass flow rate divided by the suction mass flow rate. In the test, the injection ratio varied from 0% to the maximum injection ratio at different temperature scenarios.

Table 2: Test conditions

Test	Indoor			Outdoor				Operation
	DB	WB	RH	DB	WB	RH	DP	
Extended condition	26.7°C (80°F)	19.4°C (67°F)	50.66%	46.1°C (115°F)	NA	NA	NA	Steady State Cooling
A				35.0°C (95°F)				Steady State Cooling
B		≤13.9°C (≤ 57°F)	≤21.41%	27.8°C (82°F)				Steady State Cooling
C								Steady State Cooling, dry coil
D								Cyclic Cooling, dry coil
High Temp2	21.1°C (70°F)	≤15.6°C (≤ 60°F)	≤56.42%	8.3°C (47°F)	6.1°C (43°F)	72.9%	3.7°C	Steady State Heating
High Temp1				16.7°C (62°F)	14.7°C (58.5°F)	81.1%	13.4°C	Steady State Heating
Low Temp				-8.3°C (17°F)	-9.4°C (15°F)	69.8%	-12.3°C	Steady State Heating
High Temp Cyclic				8.3°C (47°F)	6.1°C (43°F)	72.9%	3.7°C	Cyclic Heating
Frost Acc.				1.7°C (35°F)	0.6°C (33°F)	82.0%	-0.9°C	Steady State Defrost
Extended condition				-17.8°C (0°F)	NA	NA	NA	Steady State Heating

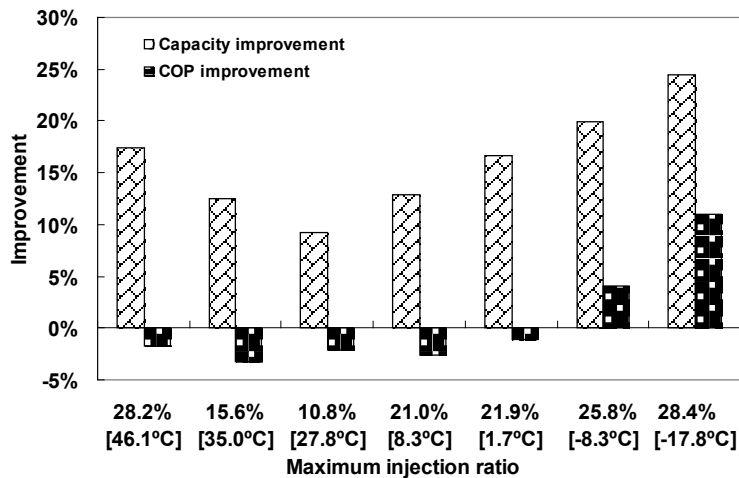


Figure 6: Performance improvements with the maximum injection ratio compared to 0% injection ratio

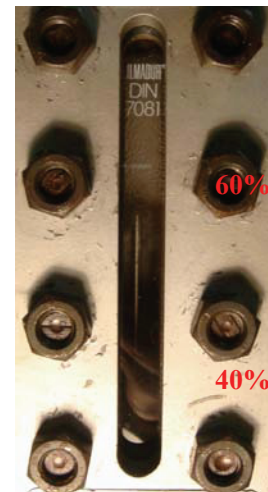


Figure 7: Two-phase refrigerant separation in the flash tank during the test

Figure 6 shows the performance improvements with the maximum injection ratio compared to the 0% injection ratio case. It can be seen that the capacity improvement was found to be significant at all temperature scenarios. The maximum capacity improvement was observed to be 24.5% with the maximum injection ratio of 28.4%. The COP improvement was found to be significant at low ambient temperatures. The maximum COP improvement was found to be 11.0% at -17.8°C.

#### 4.2 Control strategy analysis

Liquid level in the flash tank is critical to the two-phase refrigeration separation and reliable compressor operation; therefore it must be maintained to an appropriate level. Figure 7 shows the two-phase refrigerant separation in the flash tank during the test. It can be seen that there is a thick layer of bubbles above the liquid-vapor interface. This is due to the fact that the pressure in the flash tank was higher than the pressure of the injection port in the compressor. The pressure difference results in the quick “flashing” effect that refrigerant changes from liquid phase to vapor phase. From the experimental tests it was found that the liquid level should be maintained between 40% and 60% of the flash tank height. If the liquid level exceeds 60% of the flash tank height, two-phase refrigerant could be injected to the compressor. This is detrimental to the compressor, thus it should be avoided from the system control strategy point of view. On the other hand, if the liquid level decreases to be less than 40% of the tank height, then the liquid leaving the flash tank could be mixed with bubbles as well. Small amount of bubbles may not influence the lower-stage TXV operation. Large amount of bubbles, however, would cause the system to be unsteady. Therefore, two-phase refrigerant leaving the flash tank should be avoided as well.

As discussed in section 2, the main challenge for the system control is the upper-stage expansion valve control. A cost-effective method for the control is using a TXV. It's already known that a TXV would not function properly for the saturated state. From the experiments it was observed that temperature difference existed between the injected vapor and the liquid refrigerant exiting the condenser. Therefore it's possible to implement a heat exchanger between the injected vapor and the liquid exiting the condenser to introduce positive superheat to the injected vapor in order to use a TXV. Through calculations it was found that the heat transfer load of the heat exchanger were quite small at different ambient temperature conditions, therefore a tube-in-tube heat exchanger would easily suffice the heat transfer requirement. Table 3 shows the specifications of the tube-in-tube heat exchanger designed to provide the positive superheat. The liquid is assumed to flow in the inner tube, and the vapor flows in the annulus region between the inner and outer tube. Subscript “liq” refers to the liquid from the condenser outlet, and subscript “vap” refers to the injected vapor to the compressor. The heat exchanger length was also calculated. The maximum length was only found to be 1.02 m, of which the cost is negligible compared to the system using complicated and expensive EEV control.

One major consideration is that when the injected vapor is superheated, the compressor discharge temperature would tend to increase, therefore raising the compressor power consumption. This might in turn reduce the benefits of the vapor injection system. To analyze the effect of introducing positive superheat to the injected vapor on the overall system performance, a two-stage compression model was used, as shown in Figure 8.

Table 3: Specifications of the tube-in-tube heat exchanger

T <sub>ambient</sub>	T <sub>liq</sub>	T <sub>vap</sub>	P <sub>liq</sub>	P <sub>vap</sub>	MFR <sub>liq</sub>	MFR <sub>vap</sub>	Capacity	Length	Inner Diameter	Outer Diameter
°C	°C	°C	kPa	kPa	g/s	g/s	W	m	mm	mm
46.1	55.3	36.2	3666	2158	76.5	16.9	87	0.50	9.52	19.05
35	43.9	29.9	2974	1860	72.9	9.8	53	0.69		
27.8	36.7	26.1	2453	1704	69.1	6.7	39	1.02		
8.3	35.8	16.5	2372	1357	46.7	8.1	56	0.70		
-8.3	29.4	2.7	2086	914	30.6	6.3	41	0.47		
-17.8	25.3	-5.3	1928	713	22.6	5.0	31	0.39		

The lower-stage compression is shown from state 1 to state 3, and upper-stage compression is from state 5 to state 2. The vapor refrigerant is injected at state 4, and then mixed with the vapor from the lower-stage compression outlet, reaching state 5. Through the upper-stage compression, the refrigerant exits the compressor at state 2. When the superheat is introduced, the injected vapor shifts from state 4 to state 6, and after mixing with state 3, it reaches state 7. Through the high-stage compression, the refrigerant exits the compressor at state 8. The main goal is to compare the temperature difference between state 2 and state 8, and the power consumption difference between with and



without adding the positive superheat. The two-stage compression model was evaluated in Engineering Equation Solver (EES). Table 4 shows the performance variation with and without the injected vapor superheated. It can be seen that with 4 K degree of superheat, the maximum compressor discharge temperature increase is only 1.3°C, corresponding to the maximum power increase of 21.3 W. This results in a COP degradation of 0.5%. Comparing to the maximum COP gain of 11.0%, degradation of 0.5% is negligible.

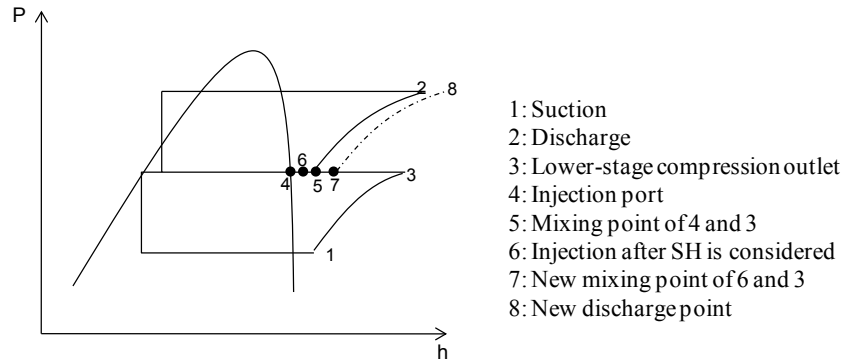


Figure 8 Two-stage compression model

Table 4: Performance variations with and without the injected vapor superheated

T <sub>ambient</sub>	MFR <sub>total</sub>	MFR <sub>inj</sub>	SH	T <sub>1</sub>	P <sub>1</sub>	P <sub>2</sub>	T <sub>2</sub>	T <sub>8</sub>	Temperature increase	COP without SH	COP with SH	COP degradation	Power increase
°C	g/s	g/s	K	°C	kPa	kPa	°C	°C	°C	-	-	%	W
46.1	76.5	16.9	4	18.8	1117	3768	97.5	98.8	1.3	2.204	2.194	-0.5	21.3
35	72.9	9.8		18.3	1083	3088	84.3	85.0	0.7	3.381	3.372	-0.3	8.7
27.8	69.1	6.7		17.8	1066	2578	72.7	73.2	0.5	4.319	4.312	-0.2	4.5
8.3	46.7	8.1		6.7	762	2443	76.2	77.1	0.9	3.670	3.660	-0.3	6.7
-8.3	30.6	6.3		-6.9	483	2128	79.8	80.8	1.0	2.880	2.873	-0.2	5.8
-17.8	22.6	5		-15.1	367	1957	88.2	89.3	1.1	2.396	2.390	-0.3	5.6

Before implementing the tube-in-tube heat exchanger to control the upper-stage expansion valve, it's necessary to experimentally verify whether introducing the positive superheat effect to the injected vapor would not cause significant performance degradation. To simulate the effect of the tube-in-tube heat exchanger, an electric heater was installed in the vapor injection line to introduce positive superheat to the injected vapor. The system was operated with different superheat settings at 35°C. Figures 9 and 10 show the discharge temperatures and total power consumptions of the experimental and EES modeling data, respectively. It can be seen that the EES modeling data matched well with the experimental data. It can also be observed that the discharge temperature and total power consumption increases were quite small with different superheat settings. Figure 11 shows the experimental results of the cooling capacity and COP degradation with the increasing degrees of superheat. It can be seen that if the degree of superheat can be controlled within 6 K, then the performance degradation would be within 1%.

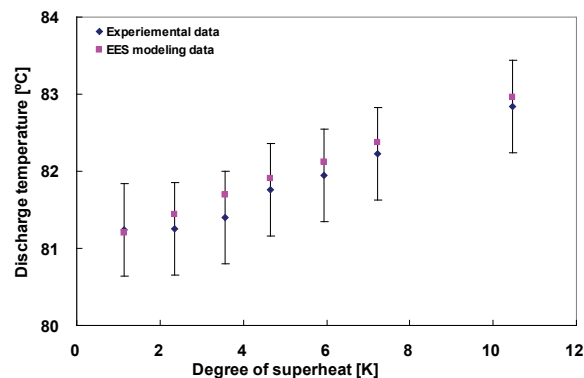


Figure 9: Experimental data and EES modeling data comparison of the discharge temperature at 35.0°C

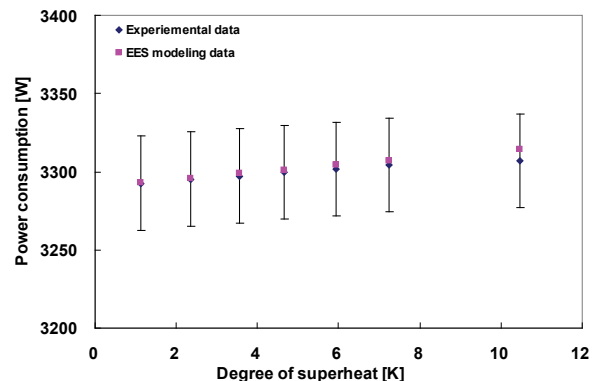


Figure 10: Experimental data and EES modeling data comparison of total power consumption at 35.0°C

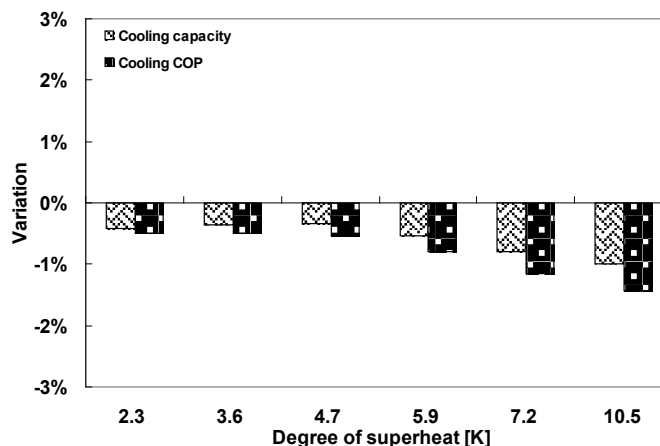


Figure 11: Experimental data of the performance degradation with increasing degrees of superheat at 35.0°C

## 6. CONCLUSIONS

This paper presents the experimental investigation on the control strategy of the vapor injection system with a flash tank using R410A as its working fluid. A prototype flash tank equipped with a sight glass was used in a vapor injection cycle to monitor the liquid refrigerant level and to visualize the two-phase refrigerant separation. From the experiments it was found that the system should be controlled in such manner that the liquid level in the flash tank is maintained between 40% and 60% of the flash tank height to ensure reliable two-phase separation, and single-phase fluid supply to the vapor injection side as well as the liquid line side. Three valves' control was discussed in detail. It was identified that the most difficult control lies in the upper-stage expansion valve control. A novel control method using a TXV for the upper-stage expansion was discussed; modeling and experimental results show that introducing positive superheat to the injected vapor would not cause significant performance degradation. It can be a cost-effective method to control the vapor injection system.

## NOMENCLATURE

COP	Coefficient of Performance	MFR	Mass Flow Rate
EES	Engineering Equation Solver	SH	Superheat
EEV	Electronic Expansion Valve	TXV	Thermostatic Expansion Valve

### Subscripts

Inj	Injection
Liq	Liquid
Vap	Vapor

## REFERENCES

1. ASHRAE Standard, Methods of testing for rating seasonal efficiency of unitary air conditioners and heat pumps, ANSI/ASHRAE 116-1995, 1995.
2. Beeton, W. L., Pham, H. M., Vapor-injected scroll compressor, ASHRAE Journal, Vol. 45, pp. 22-27, 2003.
3. Nakamura, K., High heating capacity packaged air conditioners with liquid injection cycle, Journal of Refrigeration, Vol. 82, No. 952, pp. 14-18, 2007 (In Japanese).
4. Ma, G., Chai, Q., Jiang, Y., Experimental investigation of air-source heat pump for cold regions, International Journal of Refrigeration, Vol. 26, pp. 12-18, 2003.
5. Ma, G., Chai, Q., Characteristics of an improved heat-pump cycle for cold regions, Applied Energy, Vol. 77, pp.235-247, 2004.



6. Saito, M., Packaged air conditioners that improve the heating capacity by flash injection circuit, Journal of Refrigeration, Vol. 82, No. 952, pp. 19-22, 2007 (In Japanese).
7. Wang, X., Performance investigation of two-stage heat pump system with vapor injected scroll compressor, Ph.D. Dissertation, University of Maryland College Park, 2008.

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